Geodynamics of the Gulf of Lions: implications for petroleum exploration

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ABSTRACT

The Gulf of Lions Basin forms the northern passive margin of the oceanic Provençal Basin which opened at the transition from the Aquitanian to the Burdigalian, entailing a 25-30° counter-clockwise rotation of the Corsica-Sardinia Block. The rifting phase, preceding crustal separation and the onset of sea-floor spreading, spans 6 Ma and commenced during the Late Oligocene. Oceanic crust occupies a some 200 km wide strip in the central parts of the Provençal Basin; this crust is covered by up to 6 km thick Miocene to Pleistocene sediments, including thick Messinian salts involved in diapiric structures.

The Oligo-Miocene rifts of the Gulf of Lions are superimposed on the Late Cretaceous-Early Eocene Provençal fold belt which forms part of the Pyrenean orogen. Crustal separation between Iberia and France was achieved during Mid-Aptian times. The Pyrenean orogen developed in response to convergence of Iberian micro-continent with the southern margin of France during the Alpine collision of Africa-Arabia with Europe. The Provençal fold belt evolved out of a Mesozoic rifted basin which either formed an aborted branch of Pyrenean rift or corresponded to a segment of the latter. It is here proposed that the Central Pyrenean Fault, representing the suture between Iberia and Europe, projects to the southeast of Sardinia. Consequently, we assume that the Corsica-Sardinia block remained attached to Europe during the Late Aptian to Campanian opening of the oceanic Bay of Biscay Basin.

During the Oligo-Early Miocene rifting phase, which preceded the opening of the Provençal Basin, the Pyrenean compressional structures of the Provençal fold belt were tensionally reactivated. Folded Permo-Carboniferous and Mesozoic strata form the pre-rift sequence which is at least partly preserved beneath the syn-rift sediments of the Gulf of Lions grabens. These pre-rift series contain several viable hydrocarbon source-rocks, many of which probably became over-mature for oil generation at the end of the Pyrenean orogeny. In on-shore grabens, the Oligo-Miocene syn-rift series attains thicknesses of 3-4 km and contains lacustrine source-rocks having a limited geographic distribution. The post-rift series is devoid of source-rocks.

Of the 11 exploration wells drilled in the offshore parts of the Gulf of Lions, all of which bottomed in Mesozoic strata or the basement, none

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penetrated the syn-rifted series; all wells were located on structurally high rift flanks and failed to encounter hydrocarbons. The remaining hydrocarbon potential of the Gulf of Lions must be regarded as speculative.

INTRODUCTION

The Gulf of Lions Basin forms the northern passive margin of the oceanic Provençal Basin. Development of the Gulf of Lions Basin began with the Oligo-Aquitanian rifting phase which culminated in crustal separation and the opening of the oceanic Provençal Basin, entailing a 25-30° counter-clock-wise rotation of the Corsica/Sardinia Block away from the European mainland. During this rifting event the Languedoc-Roussillon area was affected by regional extension, causing reactivation of pre-existing NE/SW trending normal faults of the Southeast France Basin and of compressional structures of the latest Cretaceous-Paleogene Pyrenean fold-and-thrust belt (Fig. 1).

Whereas in the framework of plate tectonics a consensus was quickly reached on the origin of major Atlantic-type oceans, the evolution of the Western Mediterranean remained for a long time a subject of debate. This is mainly due to the great complexity of its structural setting (Dercourt et al., 1993; Ziegler, 1988, 1994; Biju-Duval, 1984), the lack of direct information on the pre-rift sequence (boreholes) as well as to the narrowness of its basins in which thick sedimentary series obscure magnetic sea-floor anomalies, thus rendering it difficult to distinguish between thinned continental and oceanic crust.

Under such a scenario, exploration for hydrocarbons commenced in the off-shore parts of the Gulf of Lions during the late 1960's with the acquisition of regional reflection seismic surveys. The impetus for this activity was given by the discovery of small oil accumulations in the on-shore Oligocene Alès and Camargue rifted basins (Gallician field) which indicated the presence a functioning petroleum system. Unfortunately, results of the eleven exploration wells drilled between 1969 (Mistral and Sirocco) and 1985 (Agde Maritime), all of which were targeted at structural highs, were very disappointing in so far as they failed to encounter any hydrocarbons.

OPENING OF THE GULF OF LIONS

Already Argand (1924), as recalled by Durand-Delga (1980) and Olivet (1988), considered the fit of the continental slopes of Catalonia, Languedoc and Provençe on the one hand, and Corsica and Sardinia on the other, as a basic argument in favour of the oceanic nature of the Provençal Basin. This hypothesis implied that the Corsica-Sardinia Block was separated from the continental margin of Southern France after the Pyrenean orogeny.

Rotation of Corsica-Sardinia Block

As early as the 1970's different methods were applied in an effort to determine the position of the Corsica-Sardinia block prior to the opening of the Provençal Basin (Fig. 2). Based on aeromagnetic data, Auzende et al. (1973) attempted to determine transform motions between Corsica, Sardinia and the French mainland. Westphal (1976), emulating Bullard et al (1965), sought the best morphological fit of the shelf edge isobaths. These early reconstructions are tantamount to describing a linear NW/SE translation of the Corsica-Sardinia Block and do not account for its 25° to 30° rotation, indicated by paleomagnetic data.

These discrepancies were emphasized by Edel (1980) who tried to reconcile both hypotheses by considering Corsica and Sardinia as separate blocks. Faced with the objections of geologists (Arthaud and Matte, 1977; Mattauer, 1973; Auzende and Olivet, 1979; Biju-Duval and Montadert, 1977), it is now proposed that Corsica and Sardinia form a single block which rotated during the opening of the Provençal Basins by a maxi-

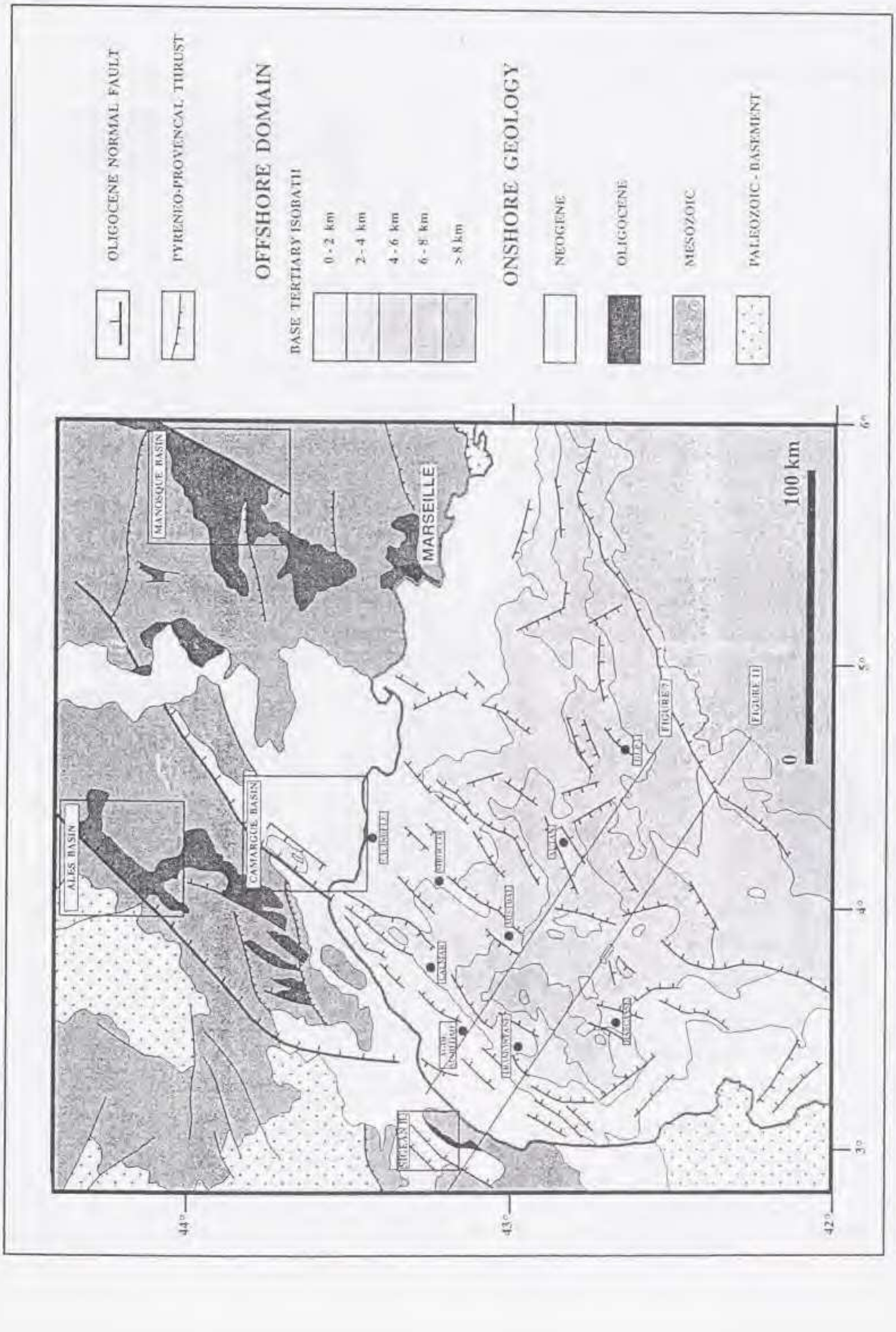

FIG. 1. Structural sketchmap of the Gulf of Lions and surrounding areas, showing location of cross-sections given in Figs. 7 and 11 and basins cited in text. Isobaths of the base-Tertiary modified after Gorini (1993).

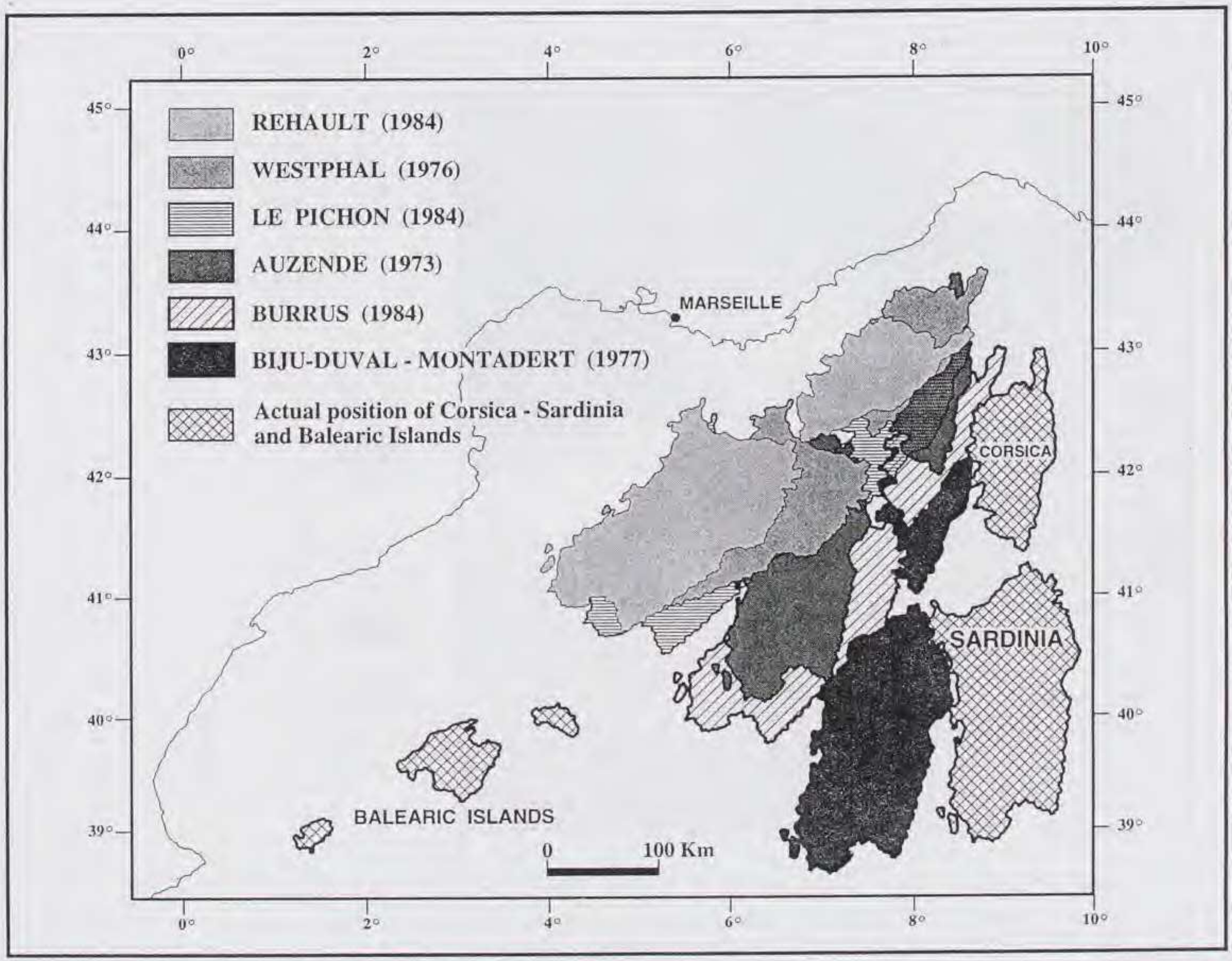

FIG. 2. Possible palaeo-position positions of the Corsica-Sardinia Block (for explanation see text)

mum of 30° about a pole located in the Gulf of Genova. Despite many uncertainties about the position of the boundary between oceanic and continental crust (Fig. 3), all reconstructions raise the problem of an apparent gap between the continental slopes of the Gulf of Lions and Western Sardinia.

After McKenzie (1978) showed that thinning of the continental crust could be achieved by stretching, this model was applied to the Gulf of Lions. New refraction-seismic data, clarifying the nature of the crust, aided in the to development of new kinematic models (Le Pichon, 1984; Burrus, 1984; Le Douaran et al., 1984; Réhault et al, 1984a, 1984b, 1985). Current studies, largely undertaken in conjunction with the Integrated Basin Studies project, integrate seismic and 3D gravimetric data and aim at proposing a new crust stretching model for the Gulf of Lions passive margin in an effort to overcome the apparent gaps in palinspastic reconstructions of the Provençal Basin.

Based on reflection-seismic surveys, Auzende et al. (1971) and Le Pichon and Sibuet (1971) suggested that a connection existed between the rotation of Corsica-Sardinia Block and the evolution of the Oligocene rifts of Western Europe. Palaeomagnetic data and studies on volcanic rocks of Sardinia provided constraints on the age of this rotation. Edel (1980) and Montigny et al. (1981) reached the conclusion that Sardinia underwent a 25 to 30° rotation during about 3 Ma at the transition from the Aquitanian to the Burdigalian, entailing a horizontal displacement of Sardinia by some 300 km.

Geological Constraints

The postulated earliest Miocene separation and rotation of the Corsica-Sardinia Block away from the southern margin of France is fully compatible with the geological data summarized below.

Upon closure of the Provençal Basin, the Palaeozoic structural, metamorphic and igneous record and zonation of the Corsica-Sardinia Block correlates readily with that of the Maures-Esterel area of Southern France. Moreover, the palaeomagnetic record of Permian volcanics supports a 30° rotation of the Corsica-Sardinia Block (Orsini et al., 1980; Lardeaux et al., 1994).

Comparison of the Mesozoic stratigraphic record of Sardinia, southeastern France (Languedoc) and Catalonia has been the subject of numerous papers (Cherchi and Schroeder, 1973, 1976; Chabrier and Fourcade, 1975; Chabrier and Mascle 1984 ; Azéma et al., 1977; Fourcade et al., 1977; Alleman, 1978; Philip and Alleman, 1982). Figure 4 provides palaeogeographic syntheses for Domerian, end Bathonian, and Valanginian times. An NW/SE trending stratigraphic cross-section, extending from the French mainland to Sardinia, datumed at the top of the Cretaceous, is given in Figure 5. It illustrates strong facies analogies between western Sardinia and the Provençal domain. Until the Middle Cretaceous, the Provençal domain and western Sardinia appear to have formed the southern margin of the rapidly subsiding intracratonic Vocontian Trough of southeastern France. In the Provençal domain, as well as in the western Sardinia (Nurra region), the Middle Cretaceous unconformity is clearly evident by more or less pronounced erosion and the deposition of bauxite. The associated uplift and deformations must be related to sinistral motions during the Aptian-Albian separation of Iberia from Europe. First indications for strongly compressional deformations occurred during the Late Cretaceous; these correlate with the early phases of the Pyrenean orogeny and the development of the flexural South Provençal Trough, the axis of which migrated in time progressively northward.

During the Paleogene, the area occupied by the future Gulf of Lions was uplifted and subject to deep erosion. Erosion products were shed northward into the continuously subsiding Eocene foredeep where they were deposited as flysch (Stanley and Mutti, 1968; Ivaldi, 1974; Jean, 1985; Ravenne et al., 1987; Vially, 1994).

Structural data on the rotation of the Corsica-Sardinia Block are much more limited and are largely based on microtectonic analyses (Cherchi and Trémolières, 1984; Letouzey et al., 1982; Letouzey, 1986). These demonstrate a counterclockwise rotation of about 30° of pre-Oligocene markers. Eocene compressional structures in Sardinia have a similar style as those in Provençe and indicate, upon palinspastic restoration, north- to northwestward directed mass transport, thus con-

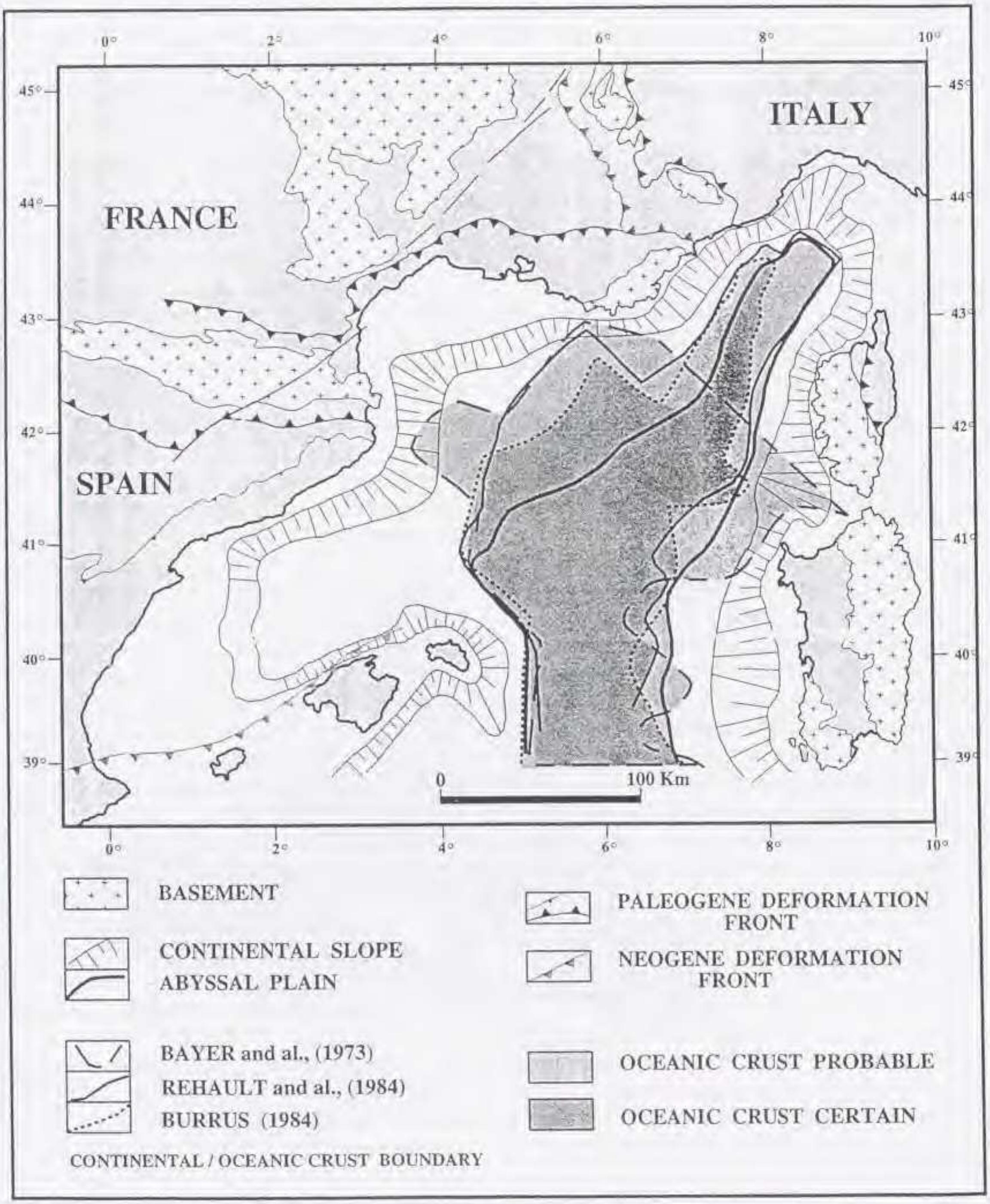

FIG. 3. Outlines of oceanic crust in Provençal Basin according to different authors.

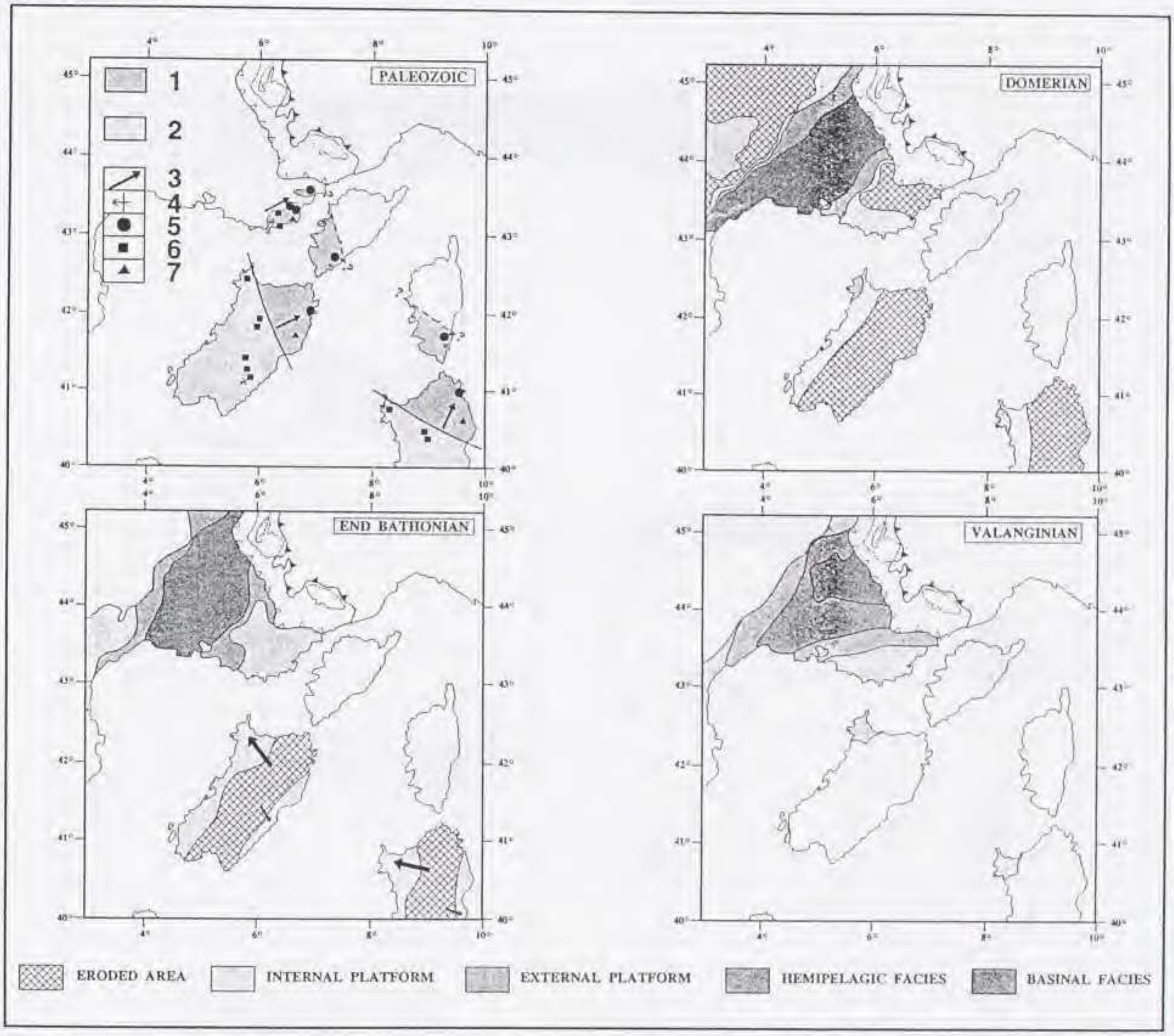

FIG. 4. Paleogeographic sketchmaps of Gulf of Lions area, showing Corsica-Sardinia Block in its pre-drift position.
Paleozoic (after Orsini et al., 1980)
1- metamorphic belt, intermediate pressure; 2- metamorphic belt, intermediate to low pressure; 3- direction of increasing degree of metamorphism; 4- fold axis; 5- granulite facies; 6- metamorphosed continental alkaline basalts; 7- metamorphosed tholeitic basalts.
Mesozoic reconstructions (after Chabrier and Fourcade, 1975; Chabrier and Mascle, 1975; Azéma et al., 1977; Fourcade et al., 1977; Alleman, 1978, Philip and Alleman, 1982; BRGM, 1984).

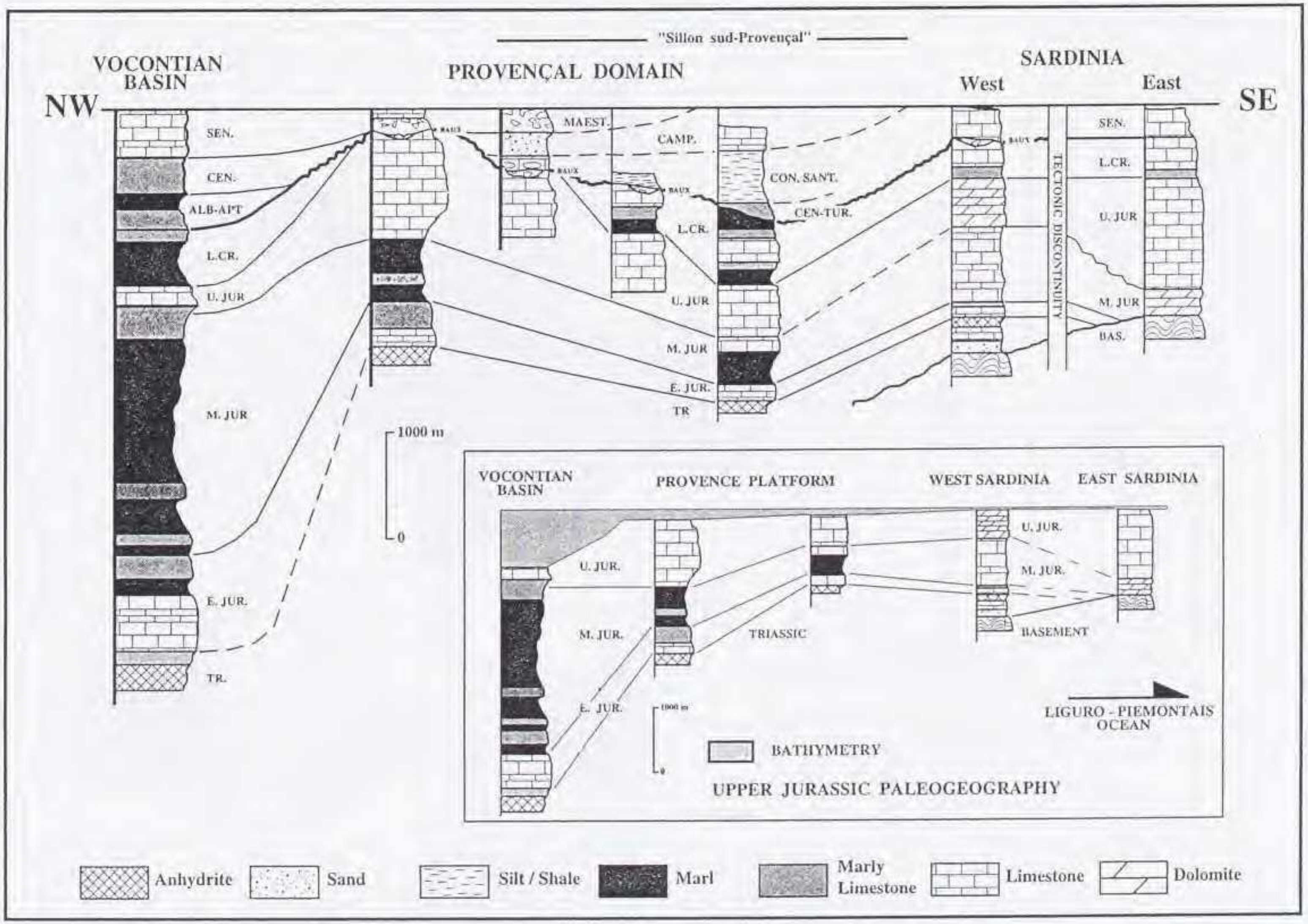

FIG. 5. Mesozoic straticraphic cross-section through Vocontian Basin, Provençal domain (after Aubouin, 1974) and Sardinia, datum top Late Cretaceous. Inset: Late Jurassic basin geometry, showing bathymetry.

firming the rotation of the Corsica-Sardinia Bock (Fig. 6; Chabrier and Fourcade, 1975; Trémolières et al., 1984).

Mechanisms Responsible for the Rotation of the Corsica-Sardinia Block

Mechanisms responsible for the Tertiary evolution of the Gulf of Lions area are clearly related to the Alpine convergence of Africa and Europe (Olivet et al., 1982, 1984; Patriat et al., 1982). However, microtectonics analyses (Letouzey and Trémolières, 1980; Bousquet and Philip, 1981; Cherchi and Trémolières, 1984; Letouzey, 1986; Villegier and Andrieux 1987) and the inventory of sea-floor magnetic anomalies (Savostin et al., 1986) indicate significant variations in their convergence pattern. In this respect, the Oligocene beginning of dextral translation between Africa and Europe may have played a significant role (Fig. 6; Ziegler, 1988).

Kinematic models for the development of the Neogene West-Mediterranean basins, involving an Oligocene change in the polarity of the subduction zone along the eastern margin of the Corsica-Sardinia Block from East-dipping to West-dipping, date back to the early 1970's (Boccaletti and Guazzone, 1972; Auzende et al., 1973; Cocozza and Jacobacci, 1975). Tapponier (1977), based on an analogy with a 'rigid/plastic' deformation model, envisaged development of the Alpine arc system and the Mediterranean basins as being the consequence of a horizontal redistribution of continental masses, induced by the collision of Africa and Europe. This view does not clash with the previous hypotheses and provides a plausible explanation for the opening of the Gulf of Lions under an overall compressional regime (see also Ziegler, 1988, 1994).

Neogene Evolution of the Gulf of Lions

Since the development of numerical models, which relate crustal stretching, thermal perturbation of the lithosphere and tectonic subsidence (McKenzie, 1978; Wernicke, 1985), the Neogene evolution of the Gulf of Lions has been considered as being governed by the dissipation of the lithospheric thermal perturbation which was induced by Oligocene rifting and early Miocene crustal separation (Steckler and Watts, 1978; Bessis, 1986; Burrus, 1989, Kooi and Cloetingh, 1992). In these models, which considered the post-Burdigalian development of the Gulf of Lions Basin to be of the passive margin-type, the Messinian 'salinity crisis' (Cita, 1973) accounts for a major incision. Messinian isolation of the Mediterranean Sea from the world oceans caused a significant lowering of the erosional base-level, inducing in the upper parts of the Gulf of Lions margin deep erosion of Miocene and older strata and in the Provençal Basin deposition of a thick salt series on oceanic crust.

Quantitative subsidence analyses by Bessis (1986) and Burrus (1989) showed that, according to numerical models, the post-rift subsidence of the Gulf of Lions Basin was much greater than implied by its syn-rift subsidence (Fig. 7a). Underlaying reasons may be seen in the initial stretching conditions of the area, as well as in its overall tectonic setting.

Standard models of lithosphere stretching (McKenzie, 1978) assume an initial crustal and lithospheric thickness of 30 and 120 km, respectively. However, in the Gulf of Lions, Oligocene rifting followed on the heel of the Pyrenean orogeny and therefore affected a thickened lithosphere and crust that probably was characterized by a considerable topographic relief. Taking this into account, stretching factors determined from syn- and post-rift subsidence agree more closely (Fig. 7a), particularly for the moderately stretched portions of the margin (stretching factor <1.8). However, a different explanation must be sought for the strongest attenuated, distal parts of the margin.

Although the Gulf of Lions has been interpreted for many years as a classical passive margin, this concept must be revised in view of the continued convergence of Europe and Africa during Neogene times. Compressional stresses can cause lithospheric deformations at wave lengths of over 100 km, resulting in uplift of broad arches and accelerated subsidence of basins (Cloetingh, 1988;

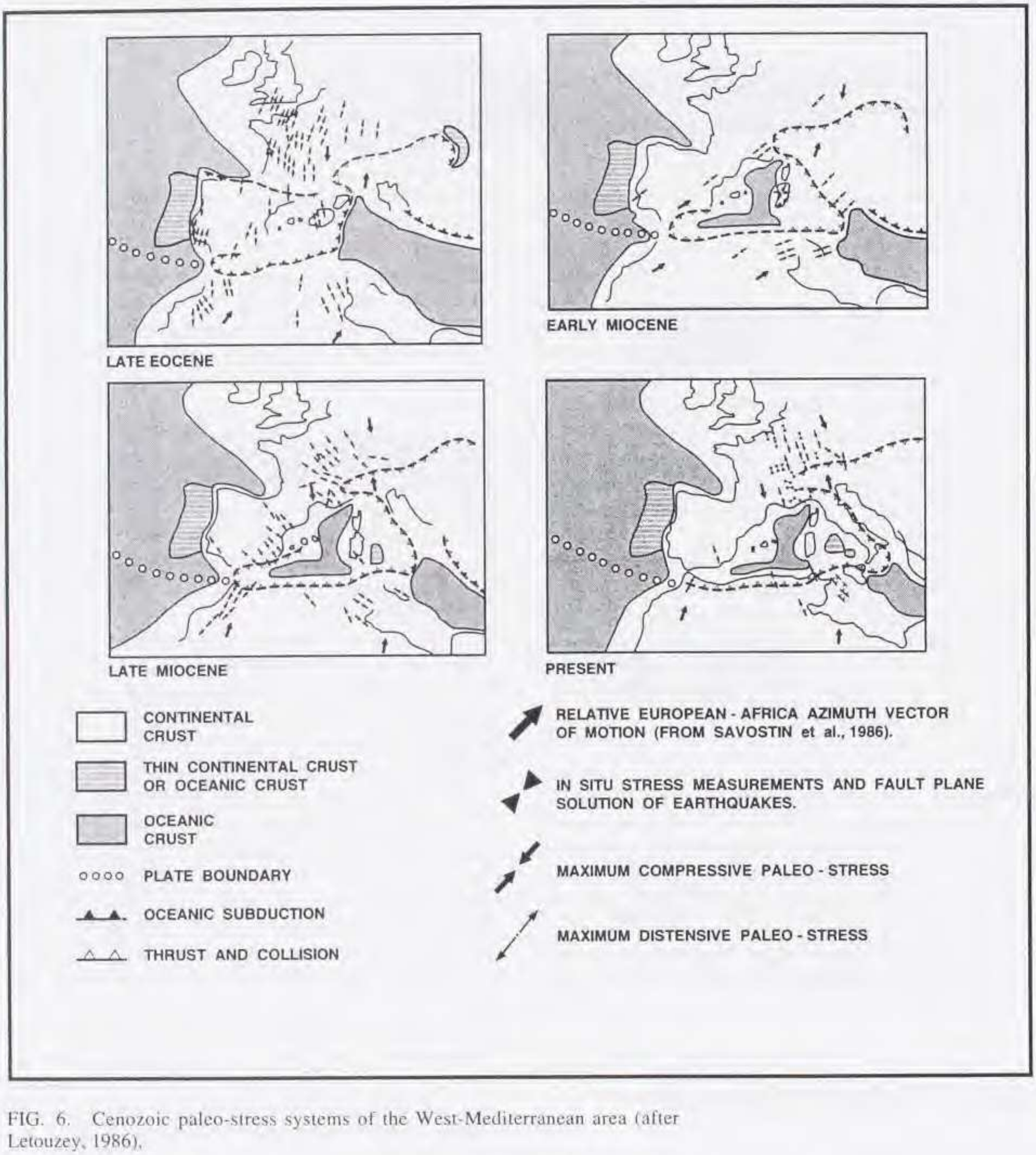

FIG. 6. Cenozoic paleo-stress systems of the West-Mediterranean area (after Letouzey, 1986).

Nikishin et al., 1993). Stress-induced accelerated subsidence of the Provençal Basin and its margins, accompanied by an exceptional rate of sediment supply, may therefore explain the observed 'abnormal' tectonic subsidence of the most extended, distal parts of the Gulf of Lions shelf and of the young, and therefore weak, oceanic lithosphere of the Provençal Basin.

GULF OF LIONS IN THE CONTEXT OF THE PYRENEAN OROGEN

During the Late Cretaceous convergence of Africa-Arabia with Eurasia, the Italo-Dinarid Block began to collide with the southern margin of Europe. At the same time subduction zones propagated westward into the West-Mediterranean domain. Convergence of Iberia with the Europe began during the Santonian and culminated in their Paleogene suturing along the Pyrenean orogen (Ziegler, 1988; Dercourt et al., 1993). The Pyrenean orogeny strongly affected also the area of the Gulf of Lions and adjacent domains.

During the Senonian first compressional deformations gave rise to the development of E-W trending folds in the Languedoc and Provençe area. However, the paroxysmal phase took place during the Eocene. Last compressional deformations were nearly synchronous with the first extensional movements which ultimately culminated in the opening of the oceanic Provençal Basin. Accepting the counter-clockwise rotation of the Corsica-Sardinia Block, we constructed two schematic palinspastic cross-sections in an attempt to clarify the relationship between Pyrenean structures on the Provençal-Languedoc-Gulf of Lions margin and those of Corsica-Sardinia (Fig. 8).

Provençal Transect (Fig. 8a)

This cross-section extends from the Vocontian domain of southeastern France to the ophiolitic nappes of Corsica; the latter represent the most internal units in this transect. Since the position of Corsica at the end of the Pyrenean orogeny is quite well known, this transect is fairly well constrained.

In the Vocontian domain, Late Cretaceous to Eocene compression gave rise to the development of E-W trending folds which are detached from the basement at a Triassic salt layer. Overall, the Vocontian domain represents an inverted extensional basin (Roure and Colletta, this volume) which is located in the foreland of the Provençal Pyrenees. Further South, in Provençe, the tectonic style changes due to a sudden thickness decrease of the Mesozoic series (Provençal Platform) and more intense shortening. Here, Eocene compression caused the development of major north-verging, thin-skinned thrust sheets. However, at Cap Sicié (Toulon region), the Palaeozoic basement is involved in the Pyrenean compressional structures.

After a some 50 km wide zone of no information, corresponding to the shelf of Ligurian Sea, the Palaeozoic basement re-appears in Corsica. According to our interpretation, the Corsican Palaeozoic massifs are allochthonous like all structures, palinspastically speaking, located south of the Cap Sicié thrust. In Corsica, a complex tectonic stack, involving basement and reduced Mesozoic and Eocene sedimentary series, representing the original sedimentary cover of eastern Corsica, is wedged between the parautochthonous Palaeozoic basement and the allochthonous "Schistes lustrés" and ophiolite nappes.

Our transect shows that we have to deal with with a typical orogenic belt which consists of an inverted basin (Vocontian Basin), an external thin-skinned thrust belt (Provençal domain), a more internal basement involving thrust belt and internal nappes consisting of obducted oceanic crust. A similarity with the Western Alps is quite apparent.

Languedoc Transect (Fig. 8b)

This cross-section, which extends from the Palaeozoic basement of the Massif Central to the East coast of Sardinia, is relatively poorly constrained. This stem from the lack of information on the nature of the substratum of the Gulf of Lions

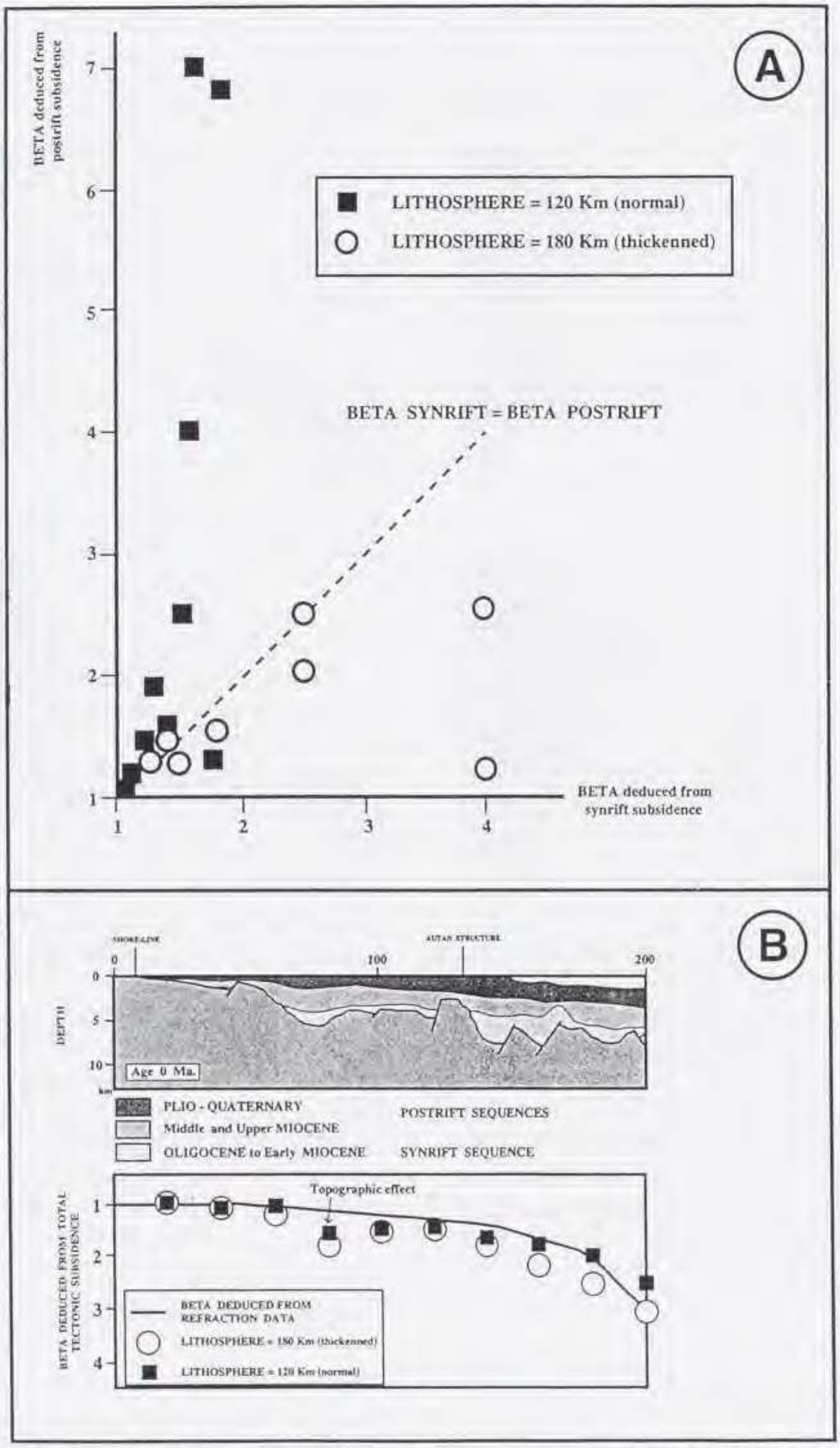

FIG. 7. a) Graph showing stretching factors (Beta) determined from syn-rift (Oligo-Aquitanian) and post-rift (Burdigalian to Present) subsidence. Black squares: after Bessis (1986), white dots: this study.
b) Comparaison between stretching factor determined from total tectonic subsidence (Bessis, 1986 and this study).

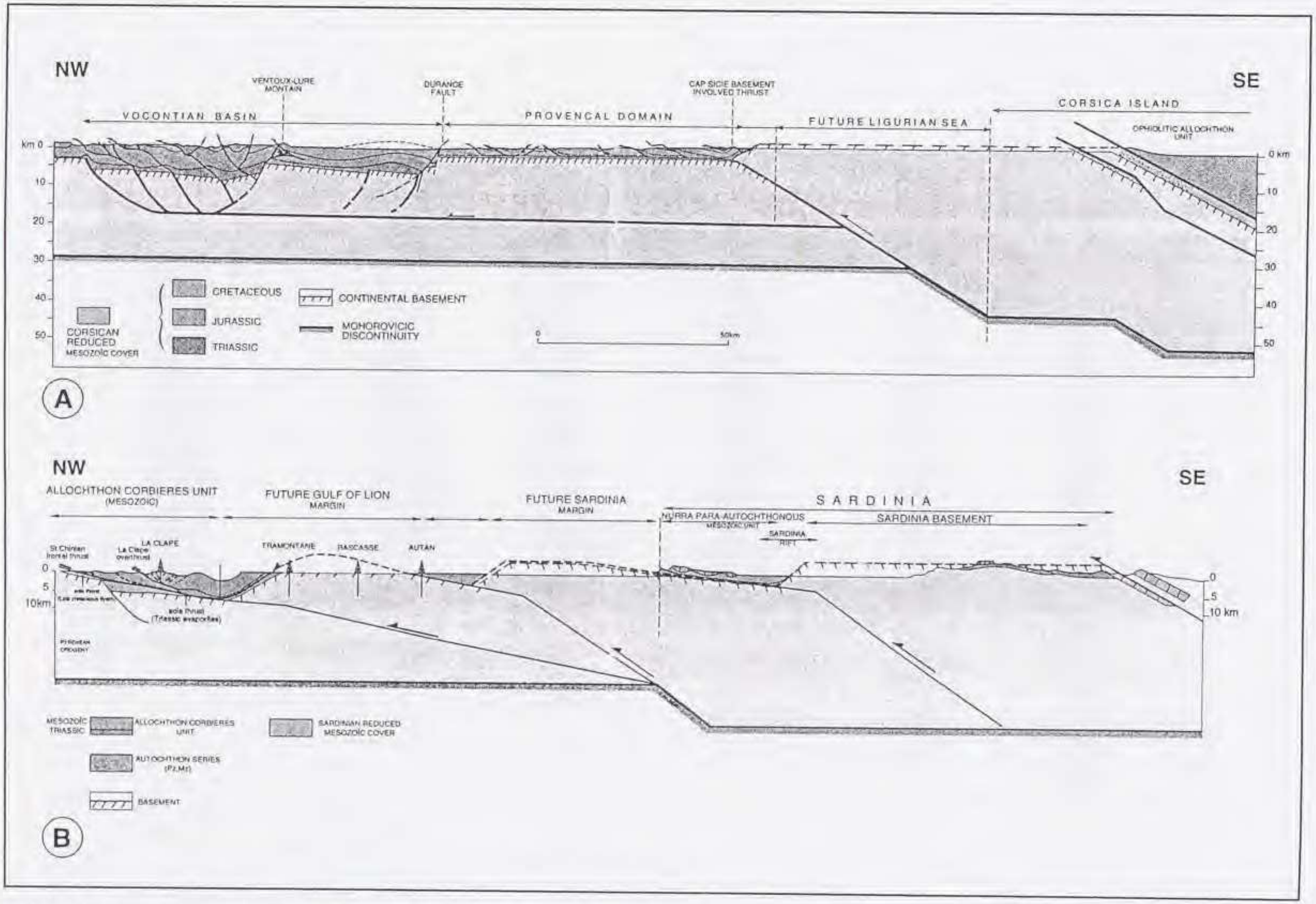

FIG. 8. Conceptual cross-sections through Gulf of Lions at end of the Pyrenean orogeny
a) Cross-section from the Vocontian Basin to Corsica.
b) Cross-section from the Massif Central to Eastern Sardinia.

and uncertainties about the pre-separation position of Sardinia.

The most external structure is the north-verging, thin-skinned Corbière nappe which accounts for about 40 km of shortening (Deville et al., 1994). This nappe may continue southward under the Gulf of Lions. The next, more internal unit, corresponds to the basement high which is defined by the wells Tramontane, Rascasse and Autan. This high is interpreted, in analogy with the Provençal transect, as a ramp-anticline which is carried by the Corbières thrust ramping down into the basement.

After a 60-70 km wide zone of no information, corresponding to the distal parts of the Gulf of Lions and the Sardinian margins, the basement surfaces again in Sardinia where it is covered by north-verging folded and thrusted Mesozoic sediments of the Nurra nappes; these were derived from eastern Sardinia. The north-verging basement imbrications of Sardinia represent the most internal elements of this tectonic edifice.

The very schematic reconstructions given in Fig. 8 raise the question about the relationship between the Corbières nappe and the basement block drilled by the Tramontane, Rascasse and Autan wells and the distribution of Mesozoic sedimentary series beneath the Gulf of Lions. Due to the presence of Mesozoic series in Sardinia, it may be inferred that, prior to the Pyrenean orogeny, Mesozoic sediments had covered the entire area of the Gulf of Lions. During the Paleogene compressional phases, the most internal area were deformed first. On the East coast of Sardinia, due to the absence of a decollement level, Mesozoic strata remained attached to the basement. At a later stage (Fig. 9), the Mesozoic cover of the Gulf of Lion was detached from its basement as the Sardinia basement back-stop advanced northward. At some stage, the Tramontane-Rascasse basement imbrication was activated, resulting in the uplift of a major high in the Gulf of Lions.

Palaeogeographic and structural reconstructions lead us to relate the Corsica-Sardinia Block to a more Alpine than a Pyrenean origin, thus raising the question of the location of the Pyrenean chain beneath the Gulf of Lions. Kinematics models (Olivet et al., 1982) generally assume that the Corsica-Sardinia Block remained attached to the Iberian plate up to Oligocene times. Hence, it was assumed that the boundary between the Iberian micro-continent and Europe projects eastwards through the Gulf of Lions to the Alpine front. However, this model raises a number of structural problems. In Corsica-Sardinia, Eocene compressional structures verge northwards when restoring this block to its pre-drift position. However, the north-vergence of the Corsica-Sardinia Paleogene structures is not compatible with a model which assumes that the Pyrenees extended through the Gulf of Lion as Corsica-Sardinia would be located along the southern margin of such a "Pyrenean" fold belt. The eastward drift of the Iberian micro-continent during Aptian to Early Senonian times, in conjunction with the opening of the North Atlantic, is thoroughly documented. Only the prolongation of the axial zone of the Pyrenean range and the significance of the North Pyrenean Fault, marking the suture between Iberia and Europe, raises problems. This leads us to propose that the Iberia/Europe plate boundary projects from the Pyrenees southeastwards and by-passes the South coast of Sardinia. In such a model, the Languedoc fold belt developed out of an intracratonic rift which formed a branch of the Mesozoic Pyrenean rift system (Fig. 10).

PETROLEUM GEOLOGY OF THE GULF OF LIONS

The Camargue, the Gulf of Lions and its Languedoc margin were explored actively, particularly on-shore, since the 1950's. On the whole, results were disappointing as only three small oil fields were discovered. However, the Gallician (7000 t produced) and the Saint-Jean de Maruéjols oil fields of in the Alès Basin demonstrate that a petroleum system can function in the Oligocene rifted basins of this area. Unfortunately, the eleven off-shore exploration wells were all dry. Yet, it must be pointed out that none of these wells penetrated the Oligocene syn-rift series.

During the last 10 years, a major effort was undertaken to re-assess the hydrocarbon potential of the Gulf of Lions and the geodynamics of its

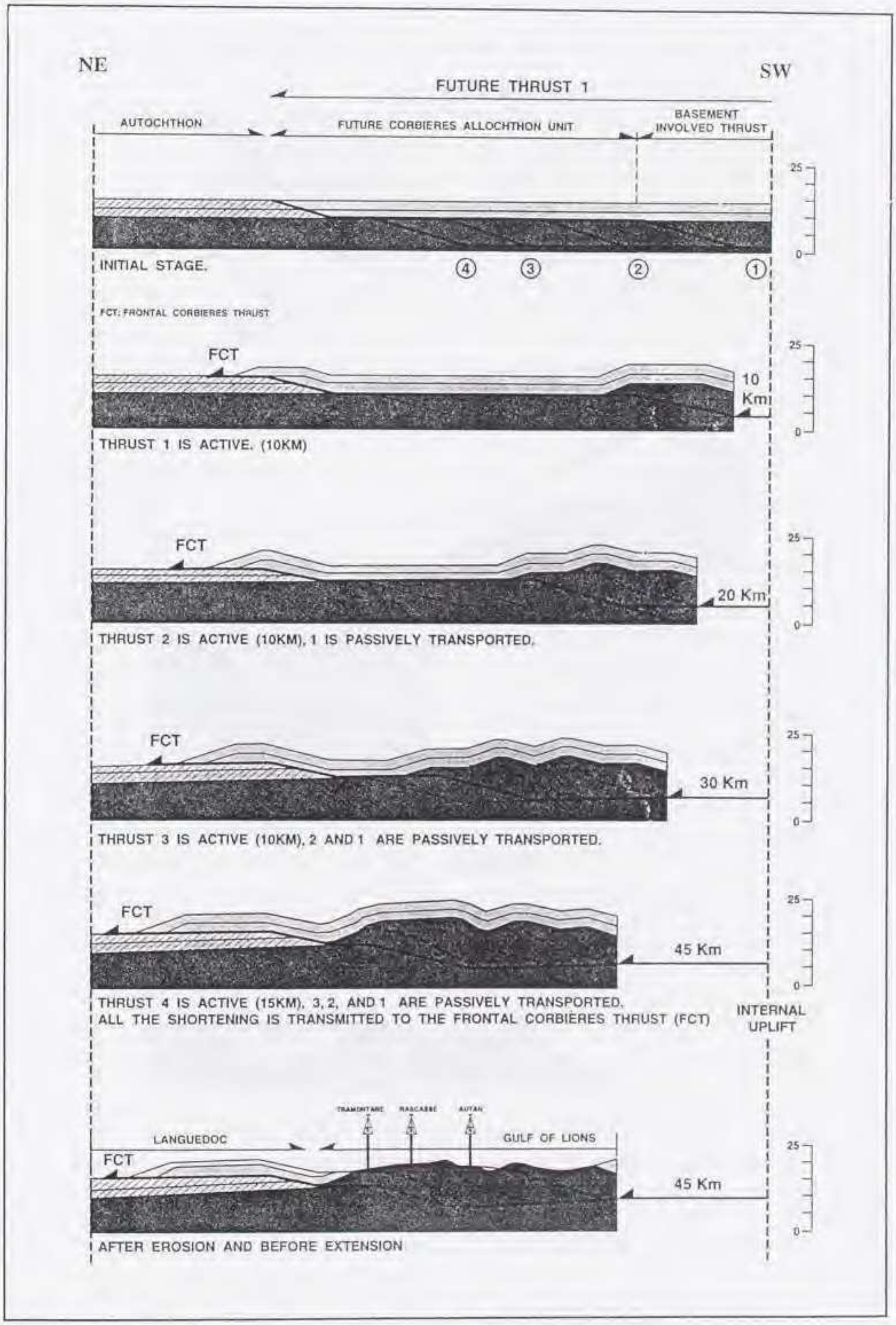

FIG. 9. Cartoons showing develpoment of Corbières allochtonous unit

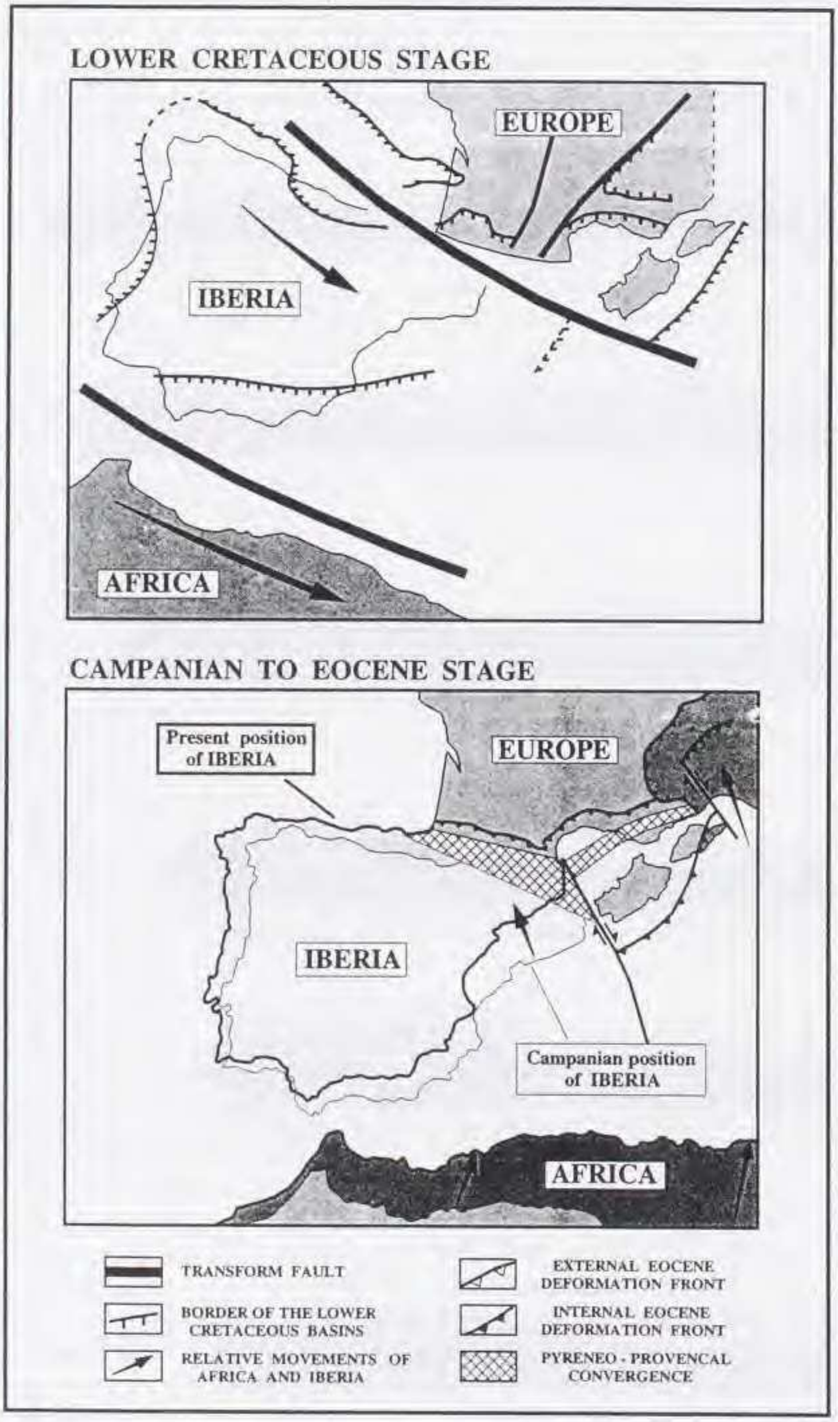

FIG. 10. Plate kinematics of Africa, Iberia, Europe during Early Cretaceous and Campanian to Eocene Pyrenean orogeny (modified after Réhault et al., 1984a)

evolution. In this respect, the availability of a network of regional deep and industry-type reflection-seismic profiles was a great advantage (De Voogd et al., 1991; Guennoc et al., 1994; Gorini et al.,1994; Pascal et al., 1994; Gaulier et al., 1994).

Regional Cross-section

The regional cross-section, given in Fig. 11, extends from the Massif Central through the Gulf of Lions to the edge of the Provençal basin and is complemented by a section through the conjugate western margin of Sardinia. The following four structural domains are recognized:

Onshore, Oligocene extensional basins developed along the Cevennes, Nîmes and Durance faults on a complex Mesozoic substratum (Roure and Colletta, this volume). In the Languedoc, the preferential extensional decollement occurs within Triassic salts which form the sole of the Corbières nappe. Reflection-seismic data reveal highly listric Oligo-Miocene normal faults, rooted in Triassic salts, which do not affect the underlying autochthonous series (Roure et al., 1992, 1994; Mascle et al., 1994; Deville et al., 1994). Although fairly superficial, these normal faults have horizontal throws of the order of 10 km. Therefore, the corresponding amount of crustal thinning must be accommodated further south. Extensional reactivation of pre-existing thrust faults is also thought to be responsible for the development of the large Clape Massif roll-over structure (Gorini et al., 1991). This structure shows evidence of Miocene (Messinian?) compressional reactivation, explaining its orographic expression. Unfortunately, poor seismic resolution at pre-Oligocene levels does not permit to map the southward extension of controlling fault systems in the near off-shore of Gulf of Lions.

On the **proximal parts of the continental shelf**, many NE/SW trending Cenozoic grabens are recognized. The largest of them, the so-called Central Graben, is located between the Tramontane and Rascasse wells, has a width of 25 km and contains up to 3000 m of sediments attributed to the Oligocene-Aquitanian (Mauffret, 1988). The geometry of these grabens is variable and complex but is generally limited by major, southeast-hading listric normal faults. The width and the depth of the Central Graben lead us to speculate that it coincides with the down-ramping of the extensional decollement level from intra-Triassic to intra-crustal levels. This zone correspond to an area where the continental crust is still only moderately attenuated, as indicated by a Moho depth of about 20 to 22 km. The boundary towards the Rascasse horst is very abrupt and is formed by a network of northwest-hading normal faults, having a cumulate throw of 4 km and more.

The **distal parts of the continental shelf**, southeast of the Rascasse horst, are characterized by a series of tilted blocks. In the hanging-wall of these blocks, syn-rift series are relatively thin whereas the total thickness of the Miocene and Plio-Peistocene post-rift series remains fairly constant. Hence, it can be assumed that during the rifting stage this area formed a high which probably had developed already during the Pyrenean compressional phase. To the southeast, the seismic facies of the basement changes drastically across a major southeast-hading normal fault and displays volcanic characteristics. This part of the margin may be either underlain by highly stretched continental crust or may correspond to the transition zone between continental and oceanic crust. In this zone, the Messinian unconformity fades out and gives way to Messinian salts which thicken uniformly seaward. These salts rest on a regionally seaward dipping monocline; their gravitational down-slope gliding gave rise to listric faults affecting the post-Messinian series.

The **conjugate Sardinia margin** is characterized by a structural style closely resembling that of the Gulf of Lions; however, the zone of block-faulting is much narrower and is dominated by east-hading antithetic normal faults (southeast-hading before rotation of Corsica-Sardinia Block). As such, the Corsica-Sardinia margin does not display the typical style of a conjugate margin (opposite polarity of normal faults) but rather forms the prolongation of the Gulf of Lions from which it is now separated by the oceanic Provençal Basin. Syn-rift series crop out only in the eastern parts of the Northwest-Sardinia Basin; its central parts are filled with post-rift sediments and substantial Miocene volcanic flows.

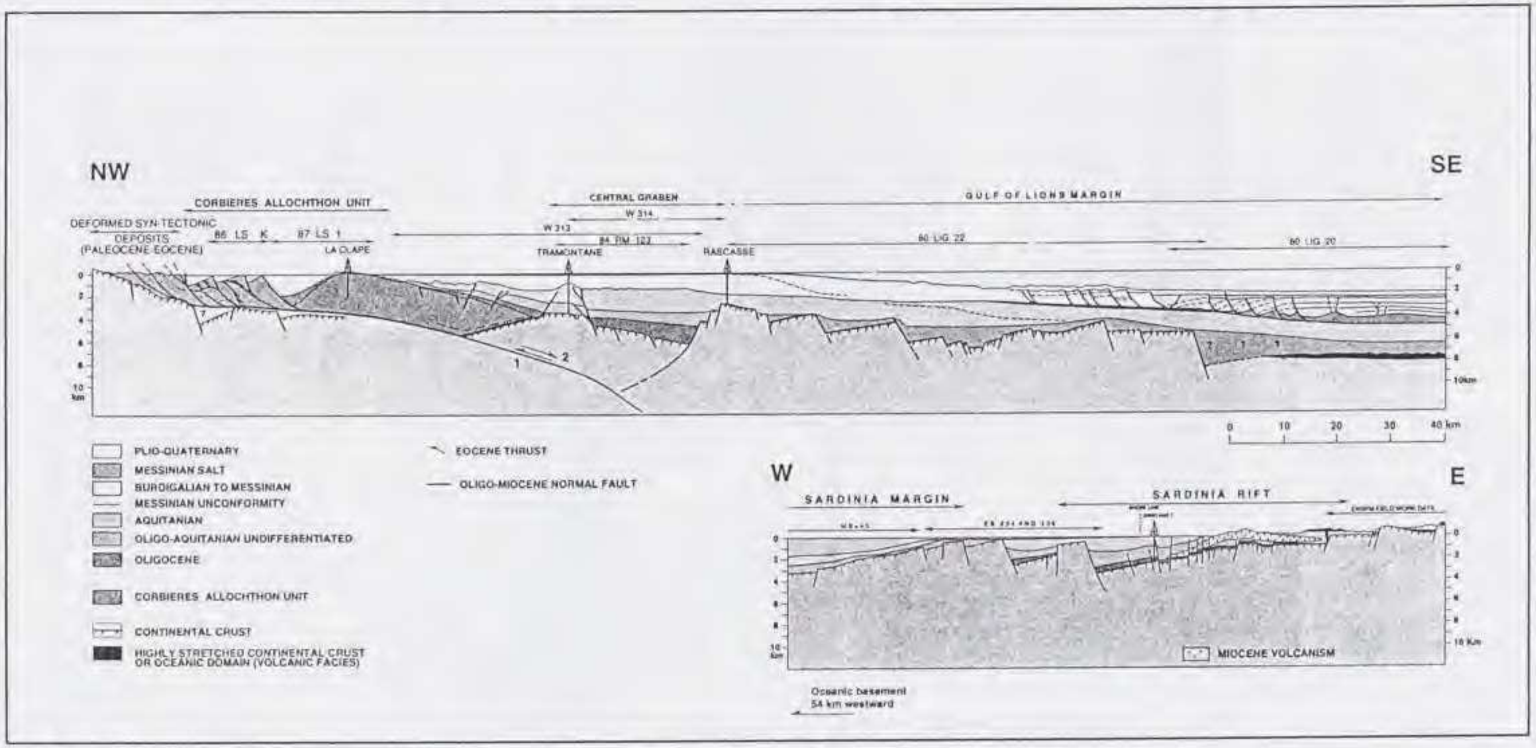

FIG. 11. Cross-section through Gulf of Lions and West-Sardinia margins (modified after after Gorini 1993, Gorini et al., 1991, 1994; Benedicto et al.,1994; Guennoc et al., 1994, Mascle et al., 1994, Séranne et al., 1995).

In recent years, mechanisms of post-orogenic extension were widely discussed (Dewey, 1988). This type of extension, which is related to body forces inherent to orogenically over-thickened crust (Bott, 1993), can give rise to the development of collapse basin and associated tectonic denudation of the deeper parts of a fold belt (Seguret et al., 1989). For the Gulf of Lions, it is difficult to determine the contribution of this mechanism to crustal extension. Yet, it is evident that tensional reactivation of pre-existing compressional faults guided the structuration of the Gulf of Lions (Gorini et al., 1991; Gorini, 1993; Benedicto et al., 1994; Séranne et al., 1995). In this respect, it is noteworthy that not only Pyrenean compressional structures, but also Late Hercynian faults, trending nearly perpendicular to the Oligocene stress direction, were reactivated (Fig. 12).

It can be assumed that in the internal parts of the Pyrenean fold belt thrusts involved all or most of the crust. Their tensional reactivation guided the zone of crustal separation and the opening of the Provençal Basin. Moreover, in areas of basement-involved thrusting, tensional reactivation of thrust-faults caused the development of wider and deeper Oligo-Miocene basins, such as the Vistrenque Trough and the Central Graben. This area is characterized by a moderately thinned crust (stretching factor <1.7), the subsidence and thermal regime of which can be modeled by an uniform stretching model. In contrast, tensional reactivation of the external parts of the Pyrenean orogen involved simple-shear detachment at a supra-crustal level (Triassic salt). Correspondingly, extensional subsidence of the Narbonne and Alès basins was not associated with a localized thermal perturbation of the lithosphere; this explains the lack of their post-rift subsidence.

Potential Reservoirs and Seals

The prediction of potential reservoir/seal pairs in the off-shore parts of the Gulf of Lions Basin relies on the results of the 11 wells drilled and on extrapolations from adjacent, geodynamically related basins. In this respect, we recapitulate that the available off-shore wells failed to encounter syn-rift series and either bottomed in Mesozoic pre-rift series or the basement.

On-shore, the **Oligo-Miocene syn-rift sequence** is confined to narrow grabens, bordered by more or less listric faults. Well data from the Camargue, Alès and Manosque/Forcalquier basins show that the Oligocene series is composed of lacustrine silty marls and limestones and logoonal evaporitic deposits, lacking good reservoir development with significant lateral continuity. The Gallician oil field produced from fractured lacustrine limestones. The absence of good reservoirs, combined with a highly waxy land-plant derived oil, accounts for poor field production.

An other model, applicable to the off-shore parts of the Gulf of Lions Basin, is provided by the Valencia Through where the syn-rift sequence consists of the lacustrine and marine organic Taraco shales, the Amposta carbonates (Lithotamium, chalk) and conglomeratic scree-slope deposits. However, in the Valencia Trough, principal reservoirs of oil accumulations are formed by karstified Mesozoic carbonates, sealed by Taraco shales and the overlaying Castellon clays (Roca and Delsegaulx, 1992; Torné et al., this volume).

In contrast to the on-shore parts of the Gulf of Lions Basin, off-shore syn-rift series may possibly contain better quality siliciclastic reservoirs due to their proximity to major basement uplifts. This concept is supported by the results of sedimentological studies in the West-Sardinia Basin, on the basis of which a depositional model was developed for potential syn-rift reservoir sands (Fig. 13; Trémolières et al., 1988). Coastal sands, intercalated with carbonates, are developed in the foot- and hanging-wall of the basement-involving Isili block; these sands have porosities of about 30%. Around the Grighine block, the presence of volcanics significantly reduces reservoir qualities. However, in the hanging-wall block, bounded by the Grighine fault, coastal sands, reworked by tides, have good porosity and are relatively clean.; tidal bar sands have porosity between 12 and 30%. Coarse, highly bioturbated carbonate sands, prograding into the basin at the outlet of the transfer corridor between the Isili and Nureci blocks,.reach thicknesses of 50 m. Across a fault, these sand bodies give laterally way to a basinal turbiditic series which is characterized intercalated sandstones and shales; individual sands have thicknesses of the order of 1-2 m.

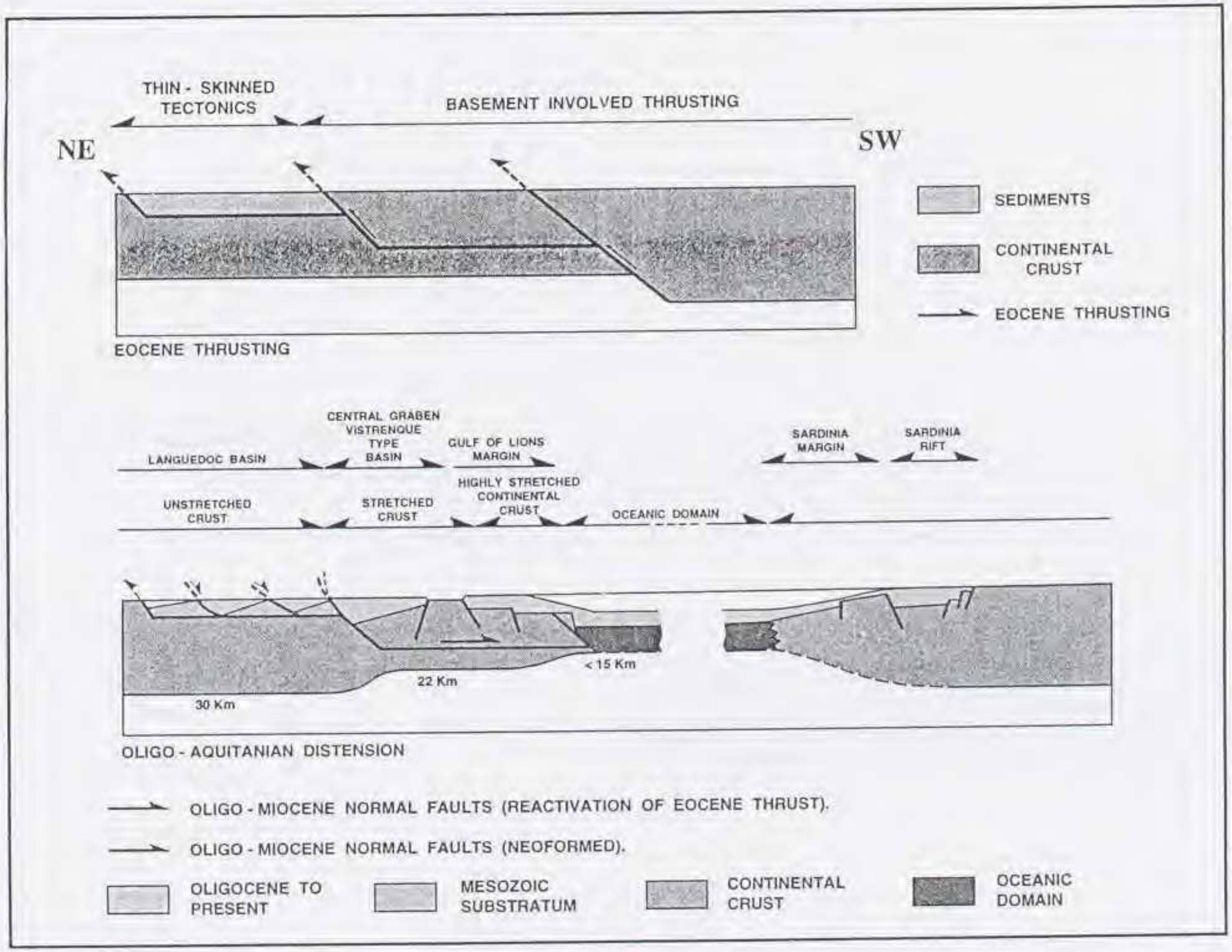

FIG. 12. Extensional model for the Gulf of Lions.

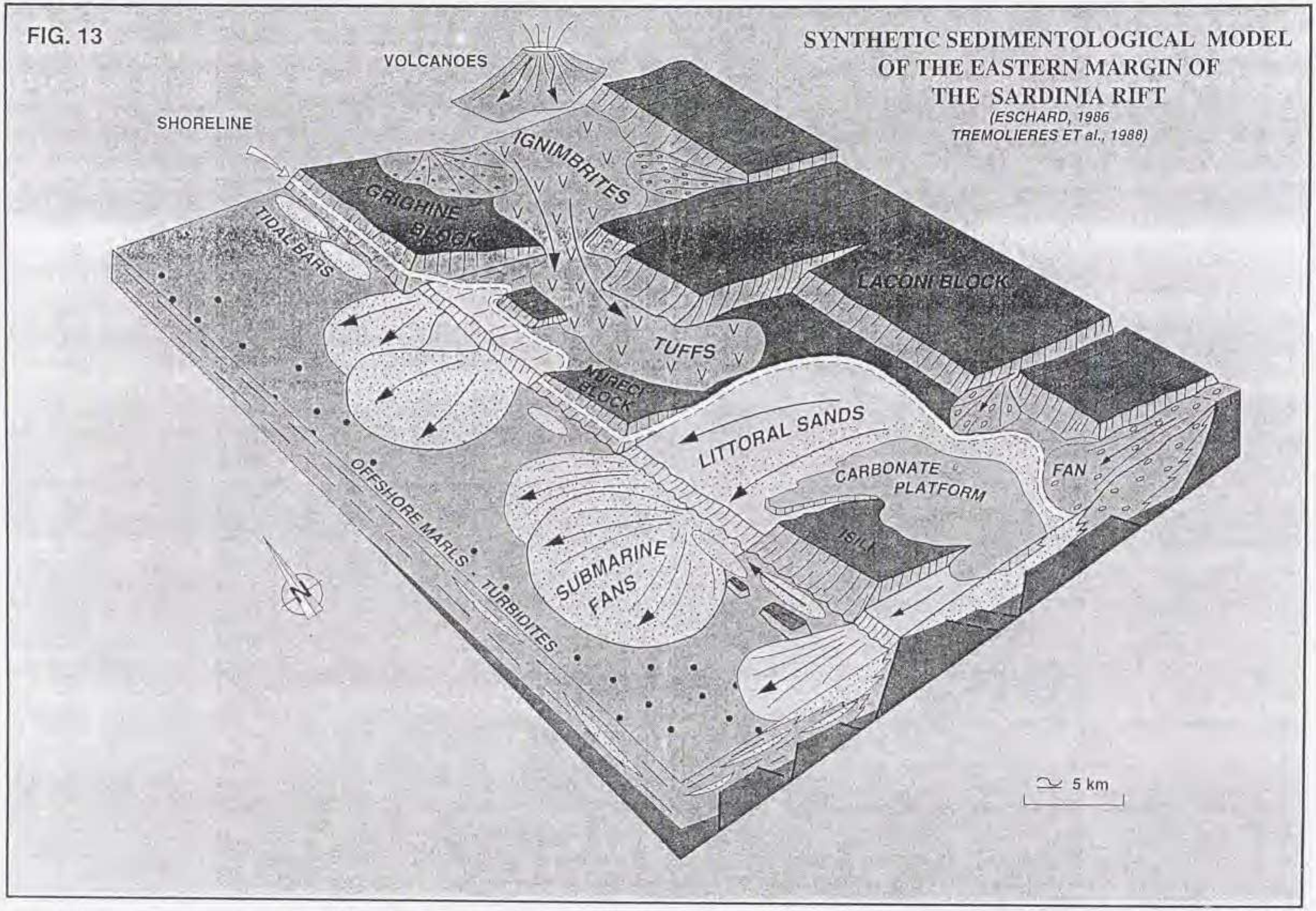

FIG. 13. Deposition model for syn-rift series of the West-Sardinian rift (Eschard, 1986; Trémolièreset al., 1988).

The **post-rift sequence** forms the largest part of the sedimentary fill of the Gulf of Lions and provides a potential seal for the syn-rift series. On the basis of the Messinian unconformity, the entire Miocene to Pleistocene sedimentary package can be subdivided into two first-order depositional sequences (Gorini, 1993). The pre-Messinian sequence commenced with the transgressive basal late Aquitanian-early Burdigalian sub-sequence which accumulated under gradually rising relative sea-levels. It is very thick in palaeo-depression and onlaps the rift topography; in platform areas this sequence is developed in a carbonate platform facies (Tramontane and Rascasse wells). This basal transgressive unit is followed by the deltaic, seaward prograding mid-Burdigalian-late Tortonian sub-sequence which accumulated under rising sea-level conditions, as indicated by well-developed top-sets. In shelf areas, the Messinian rapid drop in sea-level gave rise to a major down-cutting unconformity, whereas in deeper waters, thick salts accumulated in depositional continuity with the preceding unit. On the basis of reflection-seismic data, the Messinian drop in erosional base level was of the order of 1000 m; it included a true sea-level drop and an isostatic rebound component, induced by water unloading (Ziegler, 1988). With the post-Messinian rise in sea-level, normal marine conditions were re-established. The prograding Plio-Pleistocene sequence of the Rhône delta and its associated deep sea fan accumulated under glacio-eustatically oscillating sea-levels.

Potential Source-rocks

Potential source-rocks occur in the Oligocene syn-rift series as well as in Palaeozoic and Mesozoic pre-rift series. Although post-rift sequences are devoid of source-rock development, they may have generated biogenic gas.

Oligocene source rocks were identified in the Alès, Camargue and Manosque/Forcalquier basins where they were deposited under lacustrine to lagoonal conditions (Fig. 14). Rock-Eval analyses (Espitalié et al., 1986) indicate the presence of lacustrine type I and terrigenous type III source-rocks with an input of higher land-plants. Mixtures between type I and III source-rocks reflect very rapid lateral and vertical variation in the sedimentary environment. Lacustrine limestones have the best oil generation potential. Such limestones have a type I TOC content of up to 20% in the Camargue Basin and over 10% in the other basins. Moreover, at immature levels, these source-rocks have Hydrogen Index values higher than 730 (930 in the Camargue Trough), indicating an excellent oil generation potential. Due to the wide thickness variations of Oligocene series, the degree of maturation ranges from immaturity in the Manosque/Forcalquier Basin to the beginning of the oil window in the Alès Basin and to the gas window and overmaturation in the Camargue Through. Intercalated with these lacustrine deposits, more detrital layers can contain coals or lignites (type III), characterized by high TOC values but a relatively low Hydrogen Index, indicating a mediocre to weak oil generation potential (essentially gas). Although such levels are found throughout the Oligocene series, they mainly occur at its base where they attain a higher maturity than the shallower, oil-prone lacustrine deposits.

Stephanian coals are known from the Alès and Lodève basins. These very mature coals offer a weak petroleum potential and are essentially gas prone. **Early Permian (Autunian) lacustrine shales** occur in the Lodève Basin; they contain type I/III organic matter and are thought to have sourced the Gabian oil field (Mascle et al., 1994). Beneath the Gulf of Lions, the geographic distribution of Late Palaeozoic basins is unknown. Furthermore, Permo-Carboniferous series appear to have attained a high degree of organic maturity, partly already during the Permian.

The **Toarcian 'Schistes cartons"** have significant regional distribution and display a good residual petroleum potential. However, these shales attained overmaturity in the South-East Basin and in the Corbière nappe prior to or during the Pyrenean orogeny whereas they are still immature along the southeastern margin of the Massif Central.

Campanian oil shales (Type I/III), occurring in the Alès Basin, offer a good petroleum potential and, at present, have just entered the oil window. Campanian lignites are reported from the Provençal margin. The geographical distribution these source-rocks is, however, unknown.

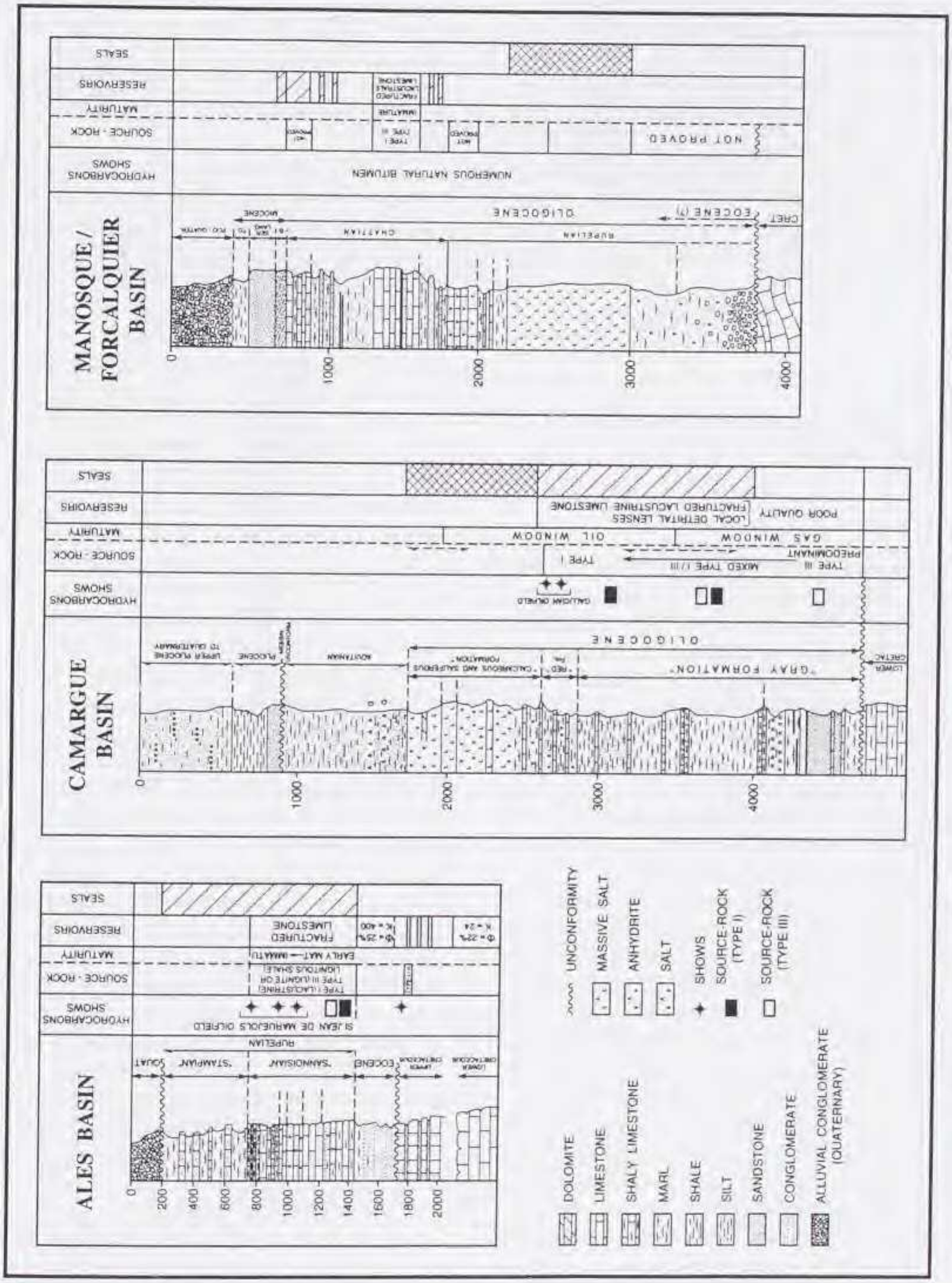

FIG. 14. Summary lithological colums for Alès, Camargue and Manosque/Forcalquier basins

The distribution of Palaeozoic and Mesozoic sediments beneath the Gulf of Lion is unknown. However, even if present, it is likely that they have reached a high level of organic maturity, either due to the depositional thickness of the Mesozoic series and/or due to tectonic overloading during the Pyrenean orogeny. Therefore, the generation potential of Palaeozoic and Mesozoic series must be heavily discounted. On the other hand, it should be noted, that the oil accumulations of the Valencia Trough were charged by source-rocks contained in the Mesozoic series as well as by the Taraco shales (Torné et al., this volume).

REMAINING HYDROCARBON POTENTIAL OF THE GULF OF LIONS

Although eleven exploration wells have been drilled in the Gulf of Lions, the petroleum potential of the syn-rift series, which on-shore contains small oil accumulations, paradoxically has not been tested. The hydrocarbon potential of this large, under-explored off-shore area (<1 well/1000 km^2) still remains to be demonstrated. New concepts developed on the evolution of this basin and the reservoir potential of the syn-rift series may provide some encouragement for further activity.directed towards the evaluation of its still untested Oligocene extensional troughs.

The available geological, geophysical and geochemical data enable us to model the evolution and maturation history of these basin (Fig. 15) Geodynamic considerations lead us to postulate that the the Gulf of Lions Basin evolved in response to uniform extension with stretching factors ranging in its different parts between 1 to 1.8. Based on this assumption, we reconstructed the heat-flow of this basin through time (McKenzie, 1978). Due to a fairly low stretching factor and a high sedimentation rate, the Gulf of Lions Basin is rather cool. The one-dimensional model constructed by means of GENEX software, shows that the oil window is only reached around a depth of 3500 m. Hence, only basins with a depth of 4000 m and more are likely to generate oil and gas, provided source-rocks are present. In such basins, whatever the type of the source-rocks (type I or III), maturation and expulsion of oil and gas commenced during Mid-Miocene to Pliocene times; at present, source-rocks have reached maximum maturity. Clearly, hydrocarbon generation and expulsion post-dates the formation and sealing of traps.

Under such a scenario, consideration must be given to potential reservoir/seal pairs involved in traps having commercially attractive volumes.

Based on the depositional model developed for the syn-rift series of the West-Sardinia Basin, **intra-Oligocene sands** (Fig. 16) may be better developed off-shore, where rift flanks are upheld by basement, than on-shore where on graben flanks Mesozoic carbonates were subjected to erosion. Such sands may occur in the basal transgressive unit and along fault scarps. Laterally these sands may interfinger with basinal shales and carbonates having a source-rock potential. Clearly, reflection-seismic data would have to be of sufficient quality to permit seismostratigraphic analysis of the syn-rift basin fill and the identification of potentially sand-prone facies. Within the syn-rift fill of Oligo-Early Miocene grabens, structural, stratigraphic or combination traps can be anticipated.

Pre-rift sediments may also provide reservoirs (Fig. 16). For instance, in the wells Calmar and Adge, oil shows were recorded in karstified Mesozoic carbonates and Palaeozoic sediments, respectively. In analogy with the Valencia Trough, karstified and fractured Jurassic carbonates can be regarded as viable reservoirs, assuming they are preserved in a down-faulted position beneath the Oligo-Early Miocene syn-rift sequence, providing for hydrocarbon charge and seals. On intermediate fault blocks, such carbonates may be sealed by the early post-rift pro-delta clays.

Bacterial gas can be expected to occur in the Rhône submarine fan delta which is characterized by high sedimentation rates. Unfortunately, so far, no bright or flat spots, gas hydrate reflections or gas chimneys have be pointed out on the available reflection-seismic data.

The remaining hydrocarbon potential of the Gulf of Lions is questionable and difficult to assess for want of a clear understanding of its pre-Oligocene evolution. Although Oligo-Miocene syn-rift sediments can have a source-rock poten-

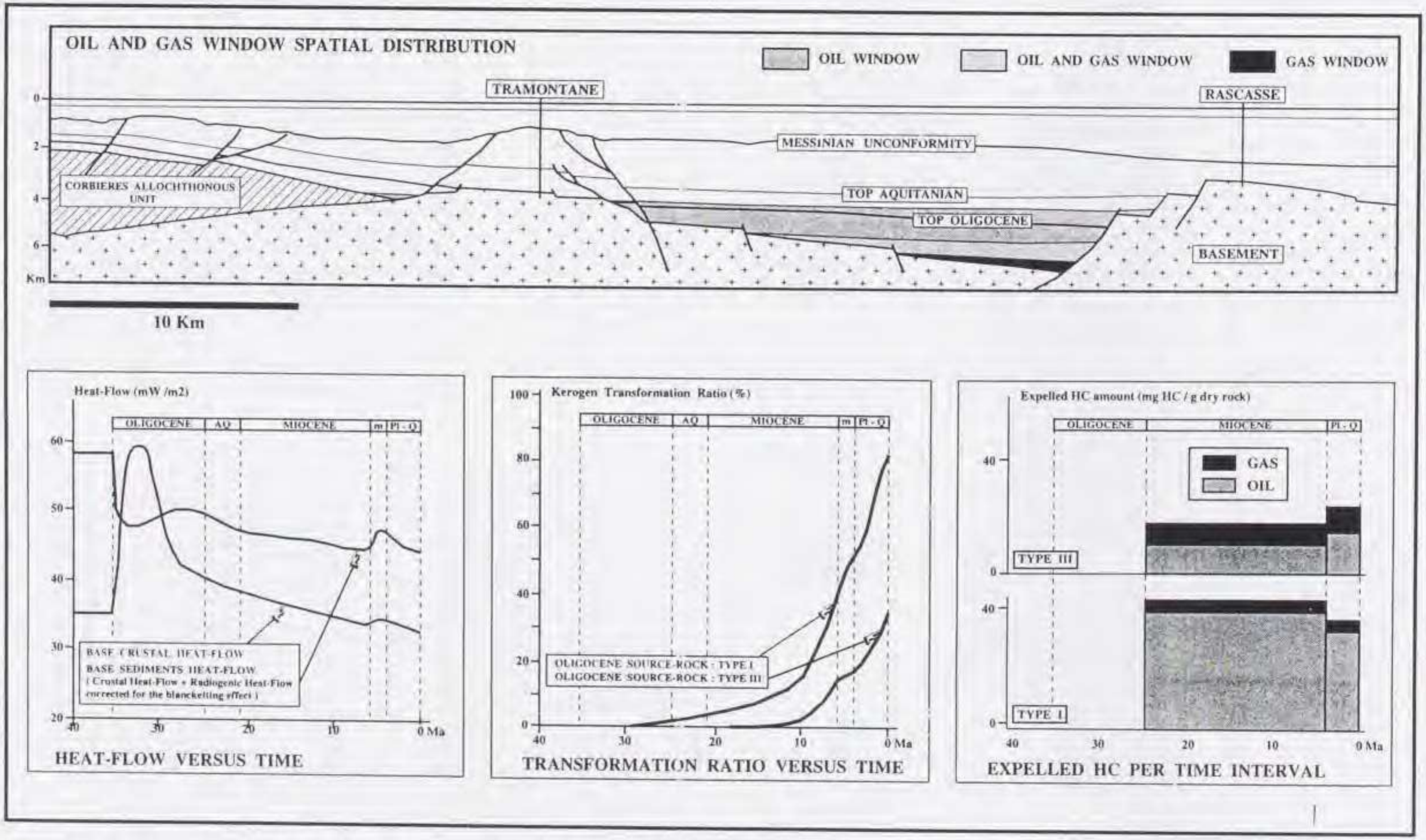

FIG. 15. Evolution of possible hydrocarbon kitchens in off-shore Gulf of Lions

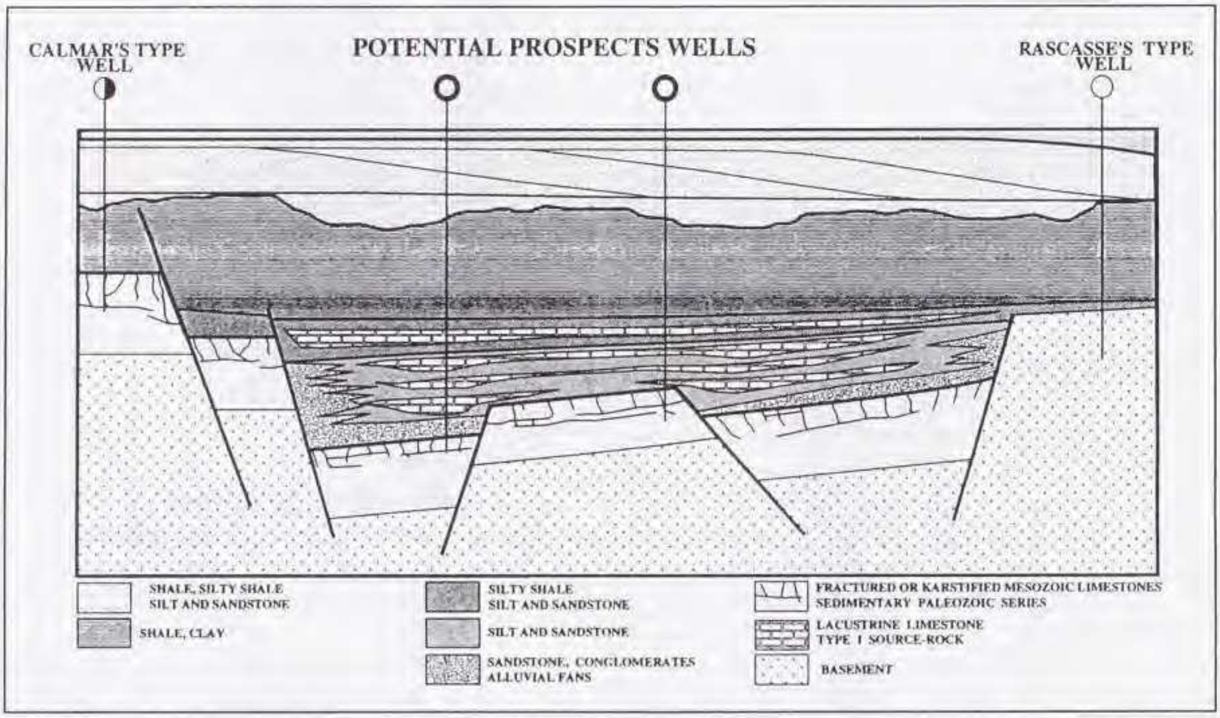

FIG. 16. Play concepts for the Gulf of Lions.

tial, the development of reservoir-seal pairs in the syn-rift series depends largely on the availability of a clastic source in the Gulf of Lions. The distribution of Mesozoic sediment, containing both potential source-rocks and reservoirs, remains an open question. As long as the resolution of reflection-seismic data cannot be improved, further hydrocarbon exploration in the Gulf of Lions.Basin will have to contend with major uncertainties and risks.

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